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16. ABSTRACT

A design model in the "Process Design Manual, Land Treatment of Municipal Wastewater" was verified as to removal of biochemical oxygen demand (BOD) and further developed to include removal of total suspended solids, ammonia, and total organic carbon by this field investigation. The model and the collected data show secondary treatment criteria for BOD, and suspended solids can be met with overland flow slopes of 15 meters in length when raw wastewater is applied and in less than 15 meters when primary wastewater is applied during warm weather conditions.

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Design model for the overland flow process

Jack L. Witherow, Bert E. Bledsoe

The overland flow process being built in more than two dozen municipalities in the U. S. has been designed using the general guidelines in the "Process Design Manual, Land Treatment of Municipal Wastewater."[1] These guidelines were developed and verified by overland flow systems treating food processing wastes and small research systems treating municipal wastewaters. Subsequent investigations[2-4] have shown these guidelines result in more application area than necessary to meet secondary treatment standards. Two similar design models are presented in the Manual[1] that determine application areas to meet specific discharge limitations for biochemical oxygen demand (BOD). These are:

$$C_s/C_o = Ae^{[(-kS)/(q^n)]} \quad (1)$$

$$M_s/M_o = Ae^{[(-kS)/(G^{1/3}\bar{q})]} \quad (2)$$

Where

C_s = BOD concentration at distance downslope S, mg/L,
C_o = initial BOD concentration, mg/L,
A = constant,
k = rate coefficient, m/h,
S = distance downslope, m,
q = applied wastewater $m^3/m \cdot h$,
n = constant,
M_s = mass of BOD at distance downslope S, kg,
M_o = mass of BOD at initial point, kg,
$\bar{q}$ = average of applied and discharged wastewater, and
G = slope grade, m/m.

The wetted application area is computed by:

$$\text{area} = QS/qP \quad (3)$$

Where

Q = average daily flow, m^3/d
P = application period, h/d, and
q and S are determined from Equations 1 or 2.

Both Equations 1 and 2 state BOD removal is a function of the travel distance of the wastewater (S) down the slope and the rate of application of the wastewater (q). The difference between models is that the first does not include slope grade, mass units of the pollutant, or an average application rate. The mass of pollutants and average application rate require flow measurements at the sample locations that were not made; therefore, the second design model was not tested. The purpose of this investigation was to verify the first model, further define the constant and rate coefficients for removal of BOD, and expand the model for use in calculating removal of other pollutants. A previous investigation[4] was unsuccessful in verifying the model because the mean concentrations of pollutants were not significantly different after the second sampling station at 10 m.

EXPERIMENTAL DESIGN AND OPERATION

The investigation was conducted at the field site of the Robert S. Kerr Environmental Research Laboratory in Ada, Oklahoma. This 10-acre site is located adjacent to the Ada wastewater treatment plant. The climate is suitable for year-round operation with minimal adjustments for severe weather. Average minimum air temperatures for all months except January are above freezing. The maximum freeze period is 20 days in 22 years of weather data, and the maximum storage requirement is estimated as 14 days by the EPA-1 computer program.[5] Precipitation averages 100 cm/a and on the average, 26 days per year have more than 1.25 cm. The maximum 24-hour rainfall with a 25-year return frequency is 18 cm. The study period lasted from July 8 through October 21, 1982. It was 77 days long to minimize temperature effects. The total rainfall during this period was 7 cm with two rainfall events (2.3 and 1.6 cm/d); these rainfalls produced runoff, but neither occurred when samples were collected. Monthly average maximum and minimum air temperatures during the study period were 35° and 9°C, respectively, and monthly average maximum and minimum soil temperatures were 33° and 18°C, respectively.

The slopes were thoroughly covered with a dense growth of Bermuda and fescue grasses. The subsoil at the selected site is a dense clay that restricts downward movement of water, which is necessary for operation in the overland flow mode. Slopes that measured 11 m by 32 m were formed at a uniform grade of 3%.

The model in an EPA design manual was verified for BOD removal and has been further developed for removal of total suspended solids, ammonia, and total organic carbon.

A raw domestic wastewater was obtained from the city sewer main, settled for a few minutes to remove grit, skimmed to remove floatables, and comminuted to a fine particle size before application to the slopes. Primary effluent was obtained from the discharge channel in the primary clarifier of the Ada municipal treatment plant. The primary effluent was constantly pumped a distance of about 200 m to a 1000-gal concrete tank at the field site. A pump located in this tank delivers the desired flow to the overland flow slopes; the unused wastewater flows back to the municipal plant through a city sewer main.

The application systems for the two wastewaters were automated to minimize time required for operation. The raw wastewater was applied on Slope 3 for 6 d/wk in no more than two 5-hour application periods per day for a total of 45 h/wk with an application rate of 0.33 $m^3/m \cdot h$. The primary wastewater was applied on Slopes 2 and 5 for 12 h/d, 6 d/wk. The application rate was 0.33 $m^3/m \cdot h$ on Slope 2 and 0.11 $m^3/m \cdot h$ on Slope 5. The hydraulic loadings on Slopes 2, 3, and 5 were 74, 46, and 24 cm/wk, respectively.

The wastewater was applied to each slope by two solid set fixed nozzles on risers 0.6 to 1.0 m long. Fan nozzles with orifices between 0.40 and 0.64 cm were used with a spray pattern of 145 deg. The pumping pressure was 100 to 140 kPa (15 to 20 psi). The first 3 m of the slope were covered with pea gravel over 152.4-μm thick black plastic to prevent soil erosion from the impact of the spray and to further distribute the flow across the width of the plot to promote sheet flow. Solids deposited on this area were occasionally removed for more even distribution of the wastewater. Wastewater had been applied on these slopes for several years during prior investigations, and the design and operation of the system were satisfactory.

Eighteen sample stations were installed by inserting 0.61-m long metal strips perpendicular to the flow direction at 3, 5, 9, 15, 23, and 30 m from the influent point on the three slopes used in this investigation. Each border was inserted 3 cm into the soil to collect the sheet flow and channel it through a plastic tube into a submerged sample container. Before sample collection, the contents, including accumulated solids, from each container were withdrawn with a vacuum system. The wastewater that accumulated in the container during the following 15–30 min was sampled for analyses. Samples were collected after about 3 hours of application when run-off volume was at a maximum and steady-state hydraulic conditions prevailed. Law, *et al.*[6] demonstrated that grab samples taken at peak flow are comparable in chemical quality to flow-proportional composite samples.

Samples were collected from each station weekly throughout the study period except on Slope 3 at 23 m from the influent, where sufficient samples could not be obtained for analyses. All samples collected during the study period were analyzed for eight chemical parameters. The following EPA methods[7] were followed: pH, 150.1; conductivity, 120.1; total suspended solids (TSS), 160.2; total phosphate as P, 365.2; Nitrate (NO_3), 353.1; Ammonia (NH_4), 350.1; 5-day biochemical oxygen demand (BOD_5), 405.1; and total organic carbon (TOC), 415.1. The analytical procedures used were selected from those published in "Methods for Chemical Analysis of Water and Wastes" 1976.[7]

RESULTS AND DISCUSSION

The mean values of the data collected are summarized in Table 1. The collected data were analyzed by three statistical

Table 1—Summary of mean values, n = 8 to 12.

	Plot 2—slope distance (m)						
	0	3	5	9	15	23	30
pH	7.4	7.7	7.9	7.7	7.8	7.7	7.7
Conductivity (μmho/cm)	1294	1232	1217	1213	1204	1200	1195
TSS (mg/L)	55	44	34	27	18	11	8
Total phosphate (mg/L)	5.9	5.4	5.4	5.7	6.1	5.6	5.5
NO_3 (mg/L)	0.04	0.03	0.04	0.06	0.15	0.8	1.4
NH_4 (mg/L)	14.9	13.0	12.2	11.9	11.8	8.2	6.3
TOC (mg/L)	45	35	29	27	22	17	12
BOD_5 (mg/L)	71	53	44	38	25	15	11
	Plot 5—slope distance (m)						
pH	7.4	7.8	7.7	7.9	7.7	7.7	7.7
Conductivity (μmho/cm)	1294	1272	1236	1262	1229	1320	1295
TSS (mg/L)	55	44	33	33	20	12	6
Total phosphate (mg/L)	5.9	5.4	5.8	5.5	5.2	4.4	4.7
NO_3 (mg/L)	0.04	0.06	0.15	0.19	0.83	1.74	1.83
NH_4 (mg/L)	14.9	12.8	10.1	10.4	7.3	4.2	1.7
TOC (mg/L)	45	38	26	22	16	12	10
BOD_5 (mg/L)	71	52	31	32	38	8	5
	Plot 3—slope distance (m)						
pH	7.4	7.6	7.8	7.7	7.8	—	8.0
Conductivity (μmho/cm)	1841	1414	1368	1405	1426	—	1380
TSS (mg/L)	238	92	34	37	13	—	10
Total phosphate (mg/L)	8.8	7.4	6.4	5.6	5.6	—	5.0
NO_3 (mg/L)	0.05	0.05	0.29	0.94	2.99	—	3.50
NH_4 (mg/L)	21.5	20.6	14.2	9.2	7.4	—	1.7
TOC (mg/L)	105	63	30	20	15	—	11
BOD_5 (mg/L)	176	100	49	35	23	—	16

techniques; these were Analysis of Variance (ANOVA), Duncan Multi-Range test of hypotheses, and linear regression analysis. The objectives of these statistics were to determine if pretreatment, slope distance, or hydraulic loading had a significant effect on concentration; if there is significant difference in mean concentrations at each of the six distances on the overland flow slopes; if Equation 1 could satisfactorily represent this data; and the constants A and k in Equation 1 to enable its use in future designs.

The data from Plots 2 and 5, which treated primary wastewater, were tested by ANOVA to determine if there was a significant effect of the model, flow, distance, and interaction between flow and distance. Detention time is directly related to distance and inversely related to flow. Table 2 shows the results in terms of significant and nonsignificant effects ($p \leq 0.05$).

The data, except for conductivity and total phosphorus, can be explained by the model, which consists of flow, distance, and their interaction. The total phosphate data are not related to either flow or distance and conductivity is only affected by flow. These plots have been used for more than 10 years and the phosphate exchange sites are likely near saturation. The data were collected during the warm seasons with high evaporation. Conductivity is related to the percent of flow evaporated. The percent evaporated would be higher at the low flow. The change in flow from 0.11 $m^3/m \cdot h$ to 0.33 $m^3/m \cdot h$ also resulted in significant change in the NO_3 and NH_3 data. The changes in ammonia and nitrate were more sensitive to overland flow conditions than any of the other parameters measured, which confirms a previous study.[6] These two parameters were the only ones significantly affected by all factors in Table 2. This significant interaction confounds the effects of flow and distance.

Five parameters (TOC, BOD_5, total phosphate, TSS, and pH) were not significantly affected by flow. This was unexpected as both Equations 1 and 2 have flow (q) inversely related to BOD removal. Although the change in flow had little effect on removal of pollutants, distance had a significant effect on all the parameters except conductivity and total phosphate. There were no significant interactions except for NH_4 and NO_3.

Distance had a significant effect in the previous study[4] but the only change of significance occurred in the first 10 m of the slope. The frequency of sampling was increased and the number of sampling stations was doubled in this study to determine if a significant change occurred throughout the slope length; four of the six stations were placed in the first half (15 m) of the slope length. The data collected were evaluated by the Duncan Multi-Range tests of hypotheses to determine if a significant difference ($p = 0.05$) in means existed between each of the six sampling stations. Table 3 provides the results.

Those pollutants that show the most consistent removal throughout the slope length are TSS, NH_3, BOD_5, and TOC. The first three (TSS, NH_3, and BOD_5) are of the most interest because they are included in discharge limitations; TOC is related to BOD_5 and confirms its removal with distance. There is no change in conductivity or total phosphate, an inconsistent change in pH, and a change in NO_3 in the last half of the slope.

The same statistical techniques were used to evaluate the data from Plot 3, which received comminuted and degritted raw wastewater. Only one application rate (0.33 $m^3/m \cdot h$) was tested and thus the ANOVA was limited to distance. All eight parameters were found significantly ($p \leq 0.05$) changed by distance. Duncan Multi-Range tests were used to further analyze the data; the results are in Table 4.

Many of the differences between Tables 3 and 4 reflect the differences in the applied wastewaters, especially in regard to the amount and nature of the solids. The lack of change in TSS after 5 m of travel and the change in total phosphate up to 9 m indicates the amount of settable solids in raw wastewater not present in the primary wastewater. Nitrate, a soluble pollutant, shows the same change in both Tables 3 and 4; that is, the nitrates

Table 2—ANOVA, primary wastewater on Plots 2 and 5.

Parameter	Model	Flow	Distance	Interaction
pH	S[a]	N	S	N
Conductivity	N	S	N	N
TSS	S	N	S	N
Total phosphate	N	N	N	N
NO_3	S	S	S	S
NH_4	S	S	S	S
BOD_5	S	N	S	N
TOC	S	N	S	N

[a] S = significant, N = nonsignificant.

Table 3—Duncan Multi-Range, primary wastewater on Plots 2 and 5.

	Slope distance (m)						
Parameter	0	3	5	9	15	23	30
pH	C[a]	A, B	A, B	A	A, B	B	A, B
Conductivity	A	A	A	A	A	A	A
TSS	A	B	C	C	D	E	E
Total phosphate	A	A	A	A	A	A	A
NO_3	D	D	D	D	C	B	A
NH_4	A	B	C	C	D	E	F
BOD_5	A	B	C	C	D	E	E
TOC	A	B	C	C	D	D, E	E

[a] The relative magnitude of means decrease from A to F.

Table 4—Duncan Multi-Range, raw wastewater on Plot 3.

	Slope distance (m)					
Parameter	0	3	5	9	15	30
pH	D[a]	C	B	B, C	B	A
Conductivity	A	B	B	B	B	B
TSS	A	B	C	C	C	C
Total phosphate	A	B	B, C	C, D	C, D	D
NO_3	C	C	C	B, C	A, B	A
NH_4	A	A	B	C	C	D
BOD_5	A	B	C	C, D	C, D	D
TOC	A	B	C	C, D	D	D

[a] The relative magnitude of means decrease from A to F.

Table 5—Intercepts (A) and rate constants (k).

$$C_s/C_o = Ae^{-(kS/\sqrt{q})}$$

	A	95% confidence limits		k (m/h)	95% confidence limits	
Total suspended solids						
Plot 2	0.92	0.86	0.99	0.038	0.035	0.040
Plot 5	0.96	0.90	1.03	0.024	0.023	0.025
Plot 3	0.44	0.38	0.50	0.056	0.051	0.061
Biochemical oxygen demand						
Plot 2	0.88	0.85	0.92	0.035	0.034	0.036
Plot 5	0.85	0.77	0.93	0.030	0.028	0.032
Plot 3	0.58	0.51	0.66	0.046	0.041	0.051
Total organic carbon						
Plot 2	0.88	0.84	0.91	0.022	0.021	0.024
Plot 5	0.85	0.81	0.89	0.016	0.015	0.018
Plot 3	0.57	0.51	0.63	0.039	0.035	0.044
Ammonia						
Plot 2	0.99	0.95	1.03	0.016	0.015	0.018
Plot 5	1.12	1.03	1.23	0.026	0.024	0.028
Plot 3	1.09	0.98	1.21	0.054	0.049	0.058

increase in concentration after 9 m of travel. Table 4 shows the changes in NH_4, BOD_5, and TOC concentrations were the most consistent throughout the slope length; the change in conductivity and pH with distance were not very meaningful.

Of the eight parameters measured at several locations on Plots 2, 3, and 5, the changes in mean concentrations with travel distance of wastewater flow were statistically significant and meaningful to design for BOD_5, TOC, TSS, and NH_4. The change in TOC was almost identical to the change in BOD_5 and verifies this most important parameter in design. These four data sets were subjected to further statistical analysis to determine the validity of the first-order kinetics of Equation 1. In Equation 1, n was set at 0.5 as shown in the "Process Design Manual,"[1] and the experimental application rate (q) for each overland flow plot was used in the data analyses. There were no replicates of the applied wastewater application rates. The constants A and k were the unknowns. Equation 1 was log transformed to a linear function; that is, $\ln C_s - \ln C_o = \ln A - (kS)/\sqrt{q}$. The values for A and k were developed by a linear regression analysis. An ANOVA made on the four pollutants and three overland flow slopes showed acceptance of Equation 1 ($p = 0.0001$). The removal of these pollutants from either raw or primary wastewater by the overland flow process is concluded to be a first-order reaction.

The values developed by the regression analysis for the intercept A and the rate coefficient k and the range of these values with 95% confidence limits are shown in Table 5.

Tests of hypotheses were made on the log of the intercept A and the rate coefficient k to determine if these constants were different than zero. In all 12 tests, the hypothesis that $k = 0$ was rejected ($p = 0.0001$). The rate coefficients are concluded to be highly significant. The hypothesis that $\ln A = 0$ was rejected in 6 of the 12 tests ($p = 0.05$). The six that were not rejected were on NH_4 from all the plots, on BOD_5 from Plot 5, and on TSS from Plots 2 and 5. Plots 2 and 5 were those that received primary wastewater. The TSS data from Plot 3 which received raw waste-

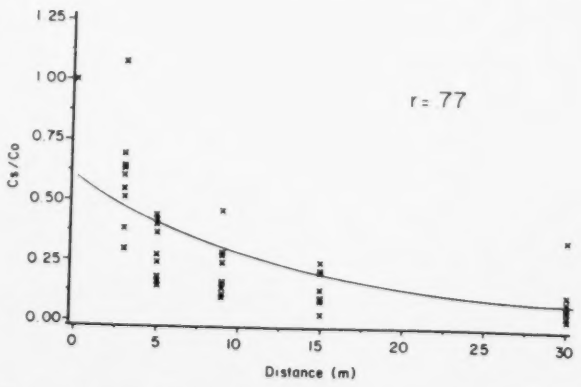

Figure 1—Regression model for BOD_5 raw wastewater on Plot 3.

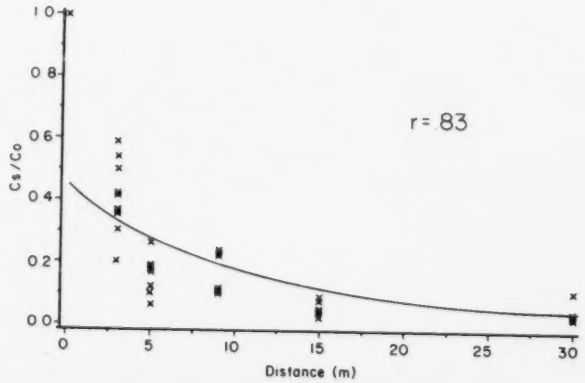

Figure 2—Regression model for TSS raw wastewater on Plot 3.

water rejected the hypotheses, ln $A = 0$ ($p = 0.0001$). The differences can be explained by the characteristics of the wastewaters applied. The raw wastewater had a mean TSS concentration of 238 mg/L while the primary wastewater had a mean of 55 mg/L. A large amount of the solids in the raw wastewater was removed in the first few feet of travel distance, and concentrations 1 m down the overland flow slope averaged 92 mg/L. Thus, the best fit equation intersects the C_s/C_o axis at 0.44, which is quite different than 1.0. The primary wastewater had an average concentration of 44 mg/L after 1 m of travel down the slope. Presettling caused the percentage of solids removed on the first 1 m of travel to be smaller. The best fit first-order equation intersects the C_s/C_o axis at 0.96, a small difference from 1.0. All three NH_4 curves intersect the C_s/C_o axis, very close to 1.0.

When the ln $A = 0$ the value of C_s/C_o at zero slope distance is 1.0. The value of C_s/C_o at zero distance should be 1.0; therefore, the value for the ln A should be zero. When it is not zero, then the first-order reaction does not accurately describe the removal during the first part of the overland flow slope. To depict this fact, data plots with the curves of best fit are shown for BOD and TSS from Plots 3 and 2 on Figures 1, 2, 3, and 4. Plot 3 received raw wastewater. Plot 2 received primary wastewater, both had applications of 0.33 $m^3/m \cdot h$. The larger removal in the first 1 m of suspended solids and related BOD is quite apparent when comparing the curves of best fit in Figures 1 and 2 with those in Figures 3 and 4.

Figures 1, 2, 3, and 4 can also be used to estimate needed slope length. For Plot 3, which treated raw wastewater, the initial TSS and BOD_5 (C_o) averaged 238 and 176 mg/L, respectively. From the curves on Figures 1 and 2, the mean concentration of both of these parameters should be less than 30 mg/L after 15 m of travel distance. For Plot 2, which treated primary wastewater, the initial TSS and BOD_5 (C_o) averaged 55 and 71 mg/L, respectively. From the curves on Figures 3 and 4, the mean concentration of both of these parameters should be less than 30 mg/L after 9 m of travel distance. The collected data confirm this to be the case on Plot 3, but not on Plot 2. On Plot 2 at 9 m, the mean values for BOD_5 and TSS were 32 and 33 mg/L, respectively. However at 15 m, BOD_5 and TSS averaged 18 and 20 mg/L, respectively. This study shows that slope lengths of 15 m are sufficient to meet secondary treatment standards when treating raw wastewater and that less than 15 m are needed when treating primary wastewater under conditions similar to those evaluated.

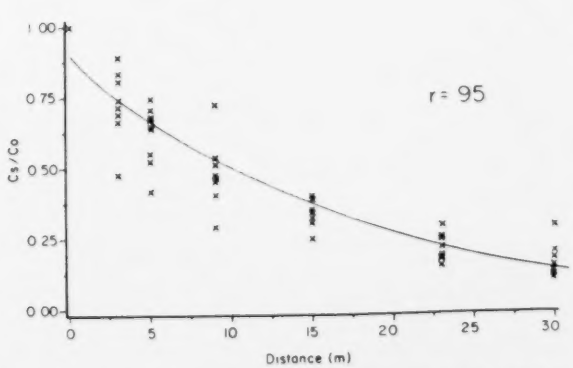

Figure 3—Regression model for BOD_5 primary wastewater on Plot 2.

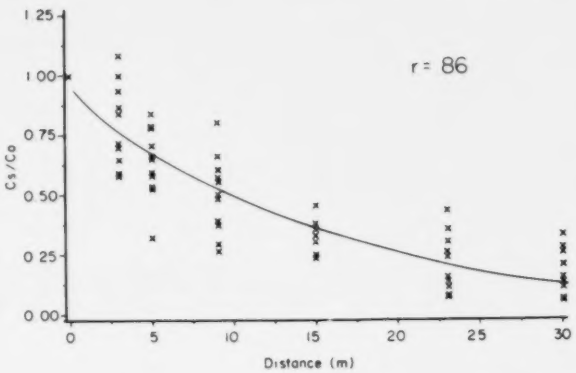

Figure 4—Regression model for TSS primary wastewater on Plot 2.

CONCLUSIONS

The following conclusions are based on warm weather evaluations:

- Increasing the application rate of primary wastewater from 0.11 to 0.33 $m^3/m \cdot h$ had a significant effect ($p \leq 0.05$) on NO_3, and NH_4 concentrations and conductivity value but not on TSS, total phosphate, BOD_5, and TOC concentrations and pH in the overland flow process.
- The length of overland flow slopes had a significant effect ($p \leq 0.05$) on BOD_5, TOC, TSS, total phosphate, NH_4, and NO_3 concentrations and on pH and conductivity values when raw wastewater was applied. Except for conductivity and total phosphate, this was also the case when primary wastewater was applied.
- Those pollutants that showed the most consistent decrease in concentration throughout the slope length were BOD_5, TSS, NH_3, and TOC.
- Removal of BOD_5, TSS, NH_4, and TOC from raw or primary municipal wastewater by the overland flow process is a first-order reaction. Linear regression analysis showing removal of these pollutants is described by $C_s/C_o = A\,e^{-kS/q}$. The intercept constant A and rate coefficient k in this equation for these four pollutants are provided in Table 5.

This equation and the collected data show secondary treatment criteria for BOD_5 and TSS can be met with overland flow slopes of 15 m when raw wastewater is applied and in less than 15 m when primary wastewater is applied during warm weather conditions.

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Authors. Jack Witherow and Bert Bledsoe were environmental engineer and research chemist, respectively, at the Robert S.

Kerr Environmental Research Laboratory, U. S. EPA. Jack Witherow is now a private engineering consultant. Correspondence should be addressed to Jack Witherow, Box 635, Gordonville, TX 76245.

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